

Time as Emergent Information Processing: A New Framework for Understanding Temporal Reality

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1 Abstract

We propose a fundamental reconceptualisation of time as an emergent property of information-processing, rather than as an intrinsic dimension of spacetime. In this framework, temporal experience arises from the observation, storage, and sequential organisation of changes by information-processing systems. Each observer constructs their own timeline through the processing of available information, resulting in observer-dependent yet physically consistent temporal realities. Our theory addresses long-standing paradoxes in relativity, offers novel insights into cosmology and consciousness, and yields testable predictions. We formalise the framework mathematically, critically compare it to existing theories of time, and outline directions for empirical and theoretical research.

Keywords: Time, Information theory, Relativity, Timeline construction, Temporal perception, Consciousness

2 Introduction

The nature of time remains one of the most fundamental and unresolved problems in both physics and philosophy [1, 2]. While the precise measurement of temporal intervals has been achieved through atomic clocks and the definition of the SI second [3], the deeper question of what time actually is continues to elude a satisfactory explanation. The Information-Processing Theory of Time (IPTT) posits that time does not exist as an independent dimension. Rather, the universe undergoes continuous changes and events, unfolding without an intrinsic temporal flow. Time, as we perceive and measure it, is an emergent cognitive construct created by information-processing systems to organise observed changes into coherent sequences [4, 5]. This ordering enables us to make sense of phenomena, understand causal relationships, and ultimately address the fundamental question of why events occur in the way they do.

Einstein's Theory of Relativity revealed that time is not absolute but rather observer-dependent [6, 7]. Yet this insight raises as many questions as it answers: Why do different observers experience different temporal orderings [8]? What gives time its apparent direction

[9, 10]? How does subjective temporal experience relate to objective physical processes [11, 12]?

This framework offers an explanation for why different observers experience different temporal orderings, what gives time its apparent direction, and how subjective temporal experience relates to objective physical processes. In the IPTT framework, ‘information’ refers specifically to observable and recordable changes in states that a system can detect and process. Temporal reality, on this view, is actively constructed rather than passively experienced [13, 14].

The core insight of this theory is that any system capable of observing changes and storing information about those changes necessarily creates its own timeline. Time, in this view, is the emergent structure that arises from the need to answer fundamental questions about causality: What happened? When did it happen in relation to other processed information? Why did it happen? The sequential organisation required to address these questions gives rise to what we experience as temporal flow and temporal ordering [15, 16]. Fundamentally, this drive to order events stems from a deeply ingrained human need to understand *why* things happen, motivating both causal reasoning and broader existential inquiry [17]. Even before formal concepts of *time* were established, humans instinctively sought to sequence changes to make sense of their world—a need that has only grown in scale and sophistication over perceived time.

The IPTT offers several advantages over existing theories. It explains observer-dependence without invoking exotic metaphysical assumptions [18]. It also resolves paradoxes concerning the origin of the universe by grounding timelines in observable information [19, 20], and it makes testable predictions about temporal perception and consciousness [4, 15, 5].

3 Theoretical Framework

3.1 Core Principles

The Information-Processing Theory of Time (IPTT) rests on four fundamental principles:

Principle I: Temporal Emergence. Time emerges from the capacity of a system to observe and record changes [21, 22]. Systems that cannot detect differences between states cannot construct timelines and therefore exist outside temporal reality.

Principle II: Observer-Relative Timeline Construction. Each information-processing system constructs its own timeline based on the available observational data. There is no absolute temporal ordering independent of these constructed timelines [18, 6].

Principle III: Information Accessibility Limits. The boundaries of any timeline are determined by the accessibility of information. Events that leave no observable traces cannot be incorporated into timelines, effectively placing them outside temporal reality for those observers [23, 9].

Principle IV: Causal Inquiry Dependence. Timeline construction is fundamentally driven by the need to establish causal relationships among detected changes. This causal ordering is not absolute but shaped by the processing capabilities of the system itself — particularly the unique neural architectures of the human brain [17, 15]. Temporal ordering emerges from organising information to answer: *What happened? When did it happen relative*

to other processed information? Why? [15, 16].

In this framework, physical reality consists solely of changes in states and discrete events, which occur sequentially due to inherent causal dependencies — not because of a pre-existing temporal dimension [22, 2]. This change-dependent reality implies that one state transition necessarily sets the conditions for the next [2, 17]. Concepts such as velocity, acceleration, and duration are not fundamental properties of an absolute time but rather human-derived representations — descriptive tools developed to quantify and predict the relationships between these underlying changes [22, 13]. Our drive to understand these causal relationships — to comprehend *why* events unfold as they do — underlies the development of complex cognitive tools such as mathematics, the concept of time itself, and collective records of the past, as embodied in books, archives, and historical narratives [13, 24].

3.2 Mathematical Formulation

The Information-Processing Theory of Time (IPTT) proposes that time is not a pre-existing dimension but an emergent construct arising from the observation and sequential organisation of changes by information-processing systems [21, 22]. This process can be formalised by considering the dynamics of information accessibility and its transformation into a coherent temporal ordering.

We define:

- $\mathcal{S}$: An information-processing system (observer).
- E : The set of all fundamental events or observable changes in the universe. These events are raw, pre-temporal occurrences that can potentially be observed.
- $\mathcal{I}_{\mathcal{S}}(t)$: The *information set* accessible to the system $\mathcal{S}$ at a given external coordinate parameter t . This set comprises all observable traces of events up to t that $\mathcal{S}$ has detected, recorded, and can access [23, 9]. Here, t serves as an abstract, external parameter against which the *rate* of information accessibility or processing can be measured, but it does not represent an intrinsic ‘flow’ of time for $\mathcal{S}$ [22].
- $\mathcal{O}_{\mathcal{S}}$: The *space of possible temporal orderings* that $\mathcal{S}$ can construct from its accessible information $\mathcal{I}_{\mathcal{S}}(t)$. Each element $o \in \mathcal{O}_{\mathcal{S}}$ is a specific sequence or partial ordering of events in $\mathcal{I}_{\mathcal{S}}(t)$.
- $\mathcal{C}(o \mid \mathcal{I}_{\mathcal{S}})$: A *causal coherence function* that quantifies the degree to which a particular ordering $o \in \mathcal{O}_{\mathcal{S}}$ establishes coherent causal relationships among the events in $\mathcal{I}_{\mathcal{S}}(t)$ [17]. This function prioritises orderings that best answer the questions: ‘What happened?’, ‘When did it happen relative to other processed information?’ and ‘Why did it happen?’ [15]. The precise form of $\mathcal{C}$ is system-dependent, reflecting the causal inference capabilities of $\mathcal{S}$ [15, 25].

3.2.1 The Timeline Construction Process

The construction of a system’s timeline, $T_{\mathcal{S}}$, is a dynamic process wherein $\mathcal{S}$ maps its accessible information into an optimally coherent temporal ordering. Formally:

$$T_{\mathcal{S}} : \mathcal{I}_{\mathcal{S}} \rightarrow \mathcal{O}_{\mathcal{S}}. \quad (1)$$

The specific constructed timeline, $T_{\mathcal{S}}^*(\mathcal{I}_{\mathcal{S}})$, is the ordering that maximises causal coherence given the available information:

$$T_{\mathcal{S}}^*(\mathcal{I}_{\mathcal{S}}) = \arg \max_{o \in \mathcal{O}_{\mathcal{S}}} \mathcal{C}(o \mid \mathcal{I}_{\mathcal{S}}). \quad (2)$$

This formulation embodies **Principle IV: Causal Inquiry Dependence**. The system continuously updates $T_{\mathcal{S}}$ as $\mathcal{I}_{\mathcal{S}}(t)$ evolves.

We model the evolution of information over t as:

$$\frac{d\mathcal{I}_{\mathcal{S}}}{dt} = \lambda(t), \quad (3)$$

where $\lambda(t)$ is the rate of information acquisition.

As new information arrives, the timeline updates according to:

$$T_{\mathcal{S}}^*(t + \Delta t) = T_{\mathcal{S}}^*(t) + \eta(t), \quad (4)$$

where $\eta(t)$ is a stochastic update term reflecting newly acquired information.

The form of $\mathcal{C}$ depends on the causal inference mechanisms of $\mathcal{S}$, particularly in biological systems such as the human brain [25, 26]. For instance, if a system cannot determine whether an event a occurred before b , its causal coherence function may ‘choose’ an ordering based on internal knowledge, learnt patterns, or external inputs (e.g., communication from others), highlighting the subjective and constructive nature of the timeline.

Examples of $\mathcal{C}(o \mid \mathcal{I}_{\mathcal{S}})$:

- **Bayesian causality:**

$$\mathcal{C}(o \mid \mathcal{I}_{\mathcal{S}}) = P(o \mid \mathcal{I}_{\mathcal{S}}) = \prod_{(e_i \rightarrow e_j) \in o} P(e_j | e_i) [17], \quad (5)$$

where $P(e_j | e_i)$ are inferred causal probabilities.

- **Information-theoretic:**

$$\mathcal{C}(o \mid \mathcal{I}_{\mathcal{S}}) = H_{\text{prior}} - H_{\text{posterior}} [22], \quad (6)$$

where H is Shannon entropy. A coherent ordering reduces uncertainty about causal structure.

- **Conflict-Minimisation:**

$$\mathcal{C}(o \mid \mathcal{I}_{\mathcal{S}}) = - \sum_{i < j} \text{Conflict}(e_i, e_j), \quad (7)$$

where $\text{Conflict}(e_i, e_j) = 1$ if the order contradicts known causal rules.

3.2.2 Observer-Relative Timelines and Information Accessibility

A fundamental consequence of this framework is the observer-relative nature of constructed timelines [18, 13]. For any two distinct information-processing systems, $\mathcal{S}_A$ and $\mathcal{S}_B$:

$$\mathcal{I}_A \neq \mathcal{I}_B \Rightarrow T_A^* \neq T_B^*. \quad (8)$$

This arises due to differences in:

1. **Information accessibility:** $\mathcal{S}_A$ and $\mathcal{S}_B$ may have access to different subsets of events or differing qualities of information, consistent with **Principle III: Information Accessibility Limits** [23].
2. **Processing capabilities:** $\mathcal{S}_A$ and $\mathcal{S}_B$ may differ in their capacities or rates of processing information, affecting both $\mathcal{I}_S(t)$ and the optimisation of $\mathcal{C}$ [25].

While differences in $\mathcal{I}_S(t)$ typically lead to distinct T_S^* , timelines can converge if differences are compensated by redundancy, quality, or causal relevance of the available information, or by relative processing efficiencies.

The rate at which information becomes accessible and is processed — and thus the rate at which T_S^* is constructed — is itself governed by physical laws [27, 28]. This constitutes the ontological component of temporal reality. Relativistic effects, for example, directly impact the physical processes underpinning information acquisition and processing, producing genuine differences in the density of events in a constructed timeline [28, 29].

3.2.3 Emergence and Non-Temporal Systems

Principle I: Temporal Emergence implies that time emerges only when detectable changes are accessible to a system [21, 22]. Formally, if a system $\mathcal{S}'$ has an information set $\mathcal{I}_{\mathcal{S}'}$ containing no distinguishable changes, then $\mathcal{S}'$ cannot construct a meaningful timeline:

$$\text{If } \mathcal{I}_{\mathcal{S}'} \text{ contains no detectable changes} \Rightarrow T_{\mathcal{S}'}^* \text{ is undefined or trivial.} \quad (9)$$

Such a system effectively exists ‘outside’ temporal reality as defined by this framework. This mathematical formulation concisely represents the IPTT, showing how its core principles lead to a dynamically constructed, observer-relative, yet physically consistent temporal reality.

3.2.4 The Dual Nature of Temporal Reality

IPTT posits that temporal reality has two complementary aspects:

- **Epistemic component:** The constructed timeline $T(\mathcal{I})$, based on processed information. This is observer-dependent and varies with available data and processing capabilities [18].
- **Ontological component:** The physical processes enabling observation and information processing, including their rates, which are subject to physical laws [27, 3].

This dual nature reconciles objective physical processes with subjective temporal experience [13, 12]. The physical processes provide the substrate for information processing, while the processing constructs the temporal framework within which these processes are interpreted [26].

4 Applications to Relativistic Physics

This framework also provides a unique lens through which to view phenomena like relativistic time dilation [6, 28, 27]. Historically, our ability to predict the future of complex systems was limited [30, 2]. However, with the development of concepts like ‘time as the rate of state change’ [21, 22] and Einstein’s theories of relativity [6], our predictive accuracy has dramatically improved.

From the IPTT perspective, time dilation does not imply that ‘time itself’ is slowing down or speeding up [2, 22]. Instead, it illustrates how the rate of physical changes and events within a system is relative to an observer’s frame of reference [6, 28]. For example, radioactive decay, understood as a sequence of physical changes, will appear to occur at a faster or slower rate to an observer in a time-dilated frame because their own rate of information-processing and the physical changes in their frame are different relative to the decaying particle’s frame [28, 27].

This predictive power is a testament to the utility of ‘time’ as a construct, not its fundamental existence [22, 2].

4.1 Special Relativity and the Twin Paradox

The famous twin paradox finds a natural and fundamental resolution within our information-processing framework [6, 31, 27]. Consider twins A and B , where twin B undertakes a high-velocity space journey while twin A remains stationary on Earth. Traditional explanations attribute the differential ageing to time dilation directly affecting the travelling twin’s biological processes [27]. Our theory offers a deeper explanation by focusing on the underlying mechanism: the inherent differences in information-processing rates and accessibility due to relativistic effects [2, 22].

For the travelling twin B :

- **Relativistic Rate Reduction:** Twin B ’s internal biological processes — which constitute their information-processing system — genuinely operate at a reduced rate due to relativistic time dilation induced by high velocity [28, 32]. This means that, for every unit of coordinate time in A ’s frame, B ’s system completes fewer fundamental processing cycles (e.g., heartbeats, cellular divisions, neural computations) [32].
- **Differential Information Accumulation:** As a direct consequence of this reduced processing rate, twin B accumulates and integrates a significantly smaller total quantity of distinct, causally relevant information-processing events into their personal timeline over the journey compared to twin A [22, 2].
- **The Role of Asymmetry:** The key to the paradox’s resolution lies in twin B ’s necessary acceleration and deceleration phases (the ‘turnaround’) to complete the journey

and reunite with twin A [31, 27]. These non-inertial periods break the symmetry between the twins' experiences, ensuring that twin B undergoes a net accumulation of fewer processed information events compared to twin A , whose information-processing occurs continuously at a higher rate in a single inertial frame.

- **External Information Integration:** While travelling at high velocity, twin B observes external events (like twin A 's clock) occurring at a different rate due to relativistic effects on information propagation and their own processing rate [6, 27]. This information is integrated into B 's constructed timeline, contributing to the perception of A 's time passing differently, but the *net* difference in their own internal timeline construction is due to the cumulative effect of their altered processing rate.

Upon reunion, both twins have constructed valid timelines based on the information their respective systems could detect, process, and organise [2]. However, the physical substrate enabling timeline construction (their biological processes) genuinely operated at different rates throughout the journey [28, 32]. The observed differential ageing is therefore a real and tangible consequence of the disparate amounts of information processing that each twin's system managed to complete. It highlights that time, as experienced and measured by a system, is inextricably linked to its capacity for information acquisition and organisation [22, 2].

4.2 Simultaneity and Temporal Ordering

The relativity of simultaneity receives a natural explanation in our framework [6, 27, 2]. Different observers do not simply measure events as simultaneous or sequential — they actually construct different temporal orderings based on when and how information reaches their information-processing systems [4, 33].

Consider observers moving relative to two spatially separated events E_1 and E_2 . Observer A might construct a timeline where E_1 occurs before E_2 , while observer B constructs a timeline where E_2 occurs before E_1 [27, 18]. Both timelines are equally valid because they emerge from the genuine differences in information accessibility between the observers [18, 2].

This eliminates the puzzle of 'which ordering is really correct' by recognising that temporal ordering is not discovered but constructed through information processing [22, 2].

For a human observer, this process concretely manifests as the **Past** comprising integrated and stored memories, forming our personal, constructed timeline [4, 34]; the **Now** being the continuous influx and processing of current sensory information, whose ceaseless updating generates the very feeling of temporal 'flow' [35, 33]; and the **Future** representing our predictions, based on accumulated knowledge and the probabilities inferred from processed information [25, 4]. The experience of 'passing time' is thus the subjective correlate of the system's ceaseless effort to integrate new information into a coherent causal narrative, as driven by ongoing sensory input [25, 4].

4.3 General Relativity and Gravitational Effects

Gravitational time dilation represents differences in information-processing rates across different gravitational potentials [7, 27, 36]. An observer in a strong gravitational field has their

physical processes — including neural activity and atomic transitions — slowed relative to observers in weaker fields [37, 29].

This results in:

- Reduced information-processing rates [4].
- Different timeline construction densities, reflecting the reduced number of recorded events per external unit of coordinate time [22, 2].
- Real, measurable differences in biological ageing and physical decay processes [28, 29].
- Consistent but observer-relative temporal experiences, where each observer perceives their own timeline as coherent and causally ordered [18, 2].

The key insight is that all observers construct valid timelines, but the rate of timeline construction varies systematically with gravitational potential [18, 22].

5 Cosmological Implications

Within the IPTT framework, the apparent sequentiality of physical events is not due to a fundamental ‘flow’ of time but rather emerges from the inherent, constrained progression of physical states [22, 38]. A system must necessarily traverse intermediate states to move from an initial to a final configuration [10, 20]. For example, motion through spacetime is fundamentally continuous and appears ‘linear’ because a system cannot ‘teleport’ or skip necessary intermediate physical changes [19, 27].

Therefore, what we perceive as a sequence of events is simply the unfolding of causally dependent changes, where each change creates the necessary physical conditions for the next — independent of any intrinsic temporal dimension [22, 38, 20].

5.1 The Origin Problem and Information Horizons

One of the most elegant aspects of the IPTT concerns cosmological origins, particularly the beginning of the universe as described by the prevailing **Big Bang cosmological model** [39]. Within the Information-Processing Theory of Time, the question ‘What happened before the Big Bang?’ becomes meaningless—not because time itself began at the Big Bang [19, 20], but because **no information from before that event can possibly reach any observer within our universe** [38].

The Big Bang, as conceived in modern cosmology, represents the earliest point from which information is accessible for constructing a coherent timeline by observers within our universe [40]. It functions as a **cosmological information horizon** [38].

This perspective resolves several long-standing cosmological paradoxes:

- **Finite Regress:** Since timeline construction is fundamentally based on accessible information, it is inherently finite for any given observer. This effectively eliminates infinite regress problems concerning origins [22].

- **Causation Paradoxes:** Questions about what ‘caused’ the Big Bang, in a temporal sense, become ill-posed within the information-accessibility framework. If no information about a ‘before’ is accessible, causal inquiry — which relies on sequential, recordable information — cannot extend beyond this horizon for observers within our universe [38].
- **Temporal Boundaries:** The universe’s ‘age’, as measured from the Big Bang, represents the maximum causal depth of constructible timelines for observers like us. It signifies the extent of our coherent, information-derived temporal reality rather than an absolute, pre-existing temporal quantity [40].

By framing the Big Bang not as the absolute start of all existence but as a fundamental information boundary for *us*, IPTT provides a consistent and powerful way to understand the limits of our temporal comprehension of the cosmos [22, 38].

5.2 Information Horizons and Black Holes

Black holes provide a compelling application of the IPTT. The event horizon represents a fundamental information boundary beyond which timeline construction breaks down for external observers [41].

For an external observer, events occurring inside the event horizon cannot contribute to their timeline construction because no information from within the horizon can escape [41]. This creates a temporal boundary where time becomes undefined — not because of gravitational effects on time itself, but because of the complete breakdown of information accessibility [41].

For an infalling observer, however, their personal timeline continues so long as they can observe and process changes in their immediate environment. Yet this timeline becomes permanently isolated from the timelines of external observers, as no information can propagate outward beyond the horizon [41].

The apparent ‘time stopping’ at the horizon for external observers thus reflects the impossibility of integrating inaccessible events into their constructed timeline, rather than a fundamental property of time itself [41].

6 Consciousness and Temporal Experience

6.1 The Distinction Between Timeline Construction and Consciousness

A crucial insight of the IPTT is the distinction between the mechanical process of timeline construction and the phenomenon of consciousness. While the brain-body system can automatically construct timelines through information-processing [42, 43], consciousness represents something qualitatively different — a reflective, questioning faculty that drives the need for timeline construction by asking, ‘Why did this happen?’ [44].

Timeline construction involves:

- Sensory information acquisition and processing [25].
- Memory storage and retrieval mechanisms [45].
- Pattern recognition and causal inference [25].
- Experience simulation and predictive modelling [25].

Consciousness, however, adds an additional dimension: the demand for causal explanation and self-referential understanding. Without consciousness to pose causal questions, there would be no evolutionary pressure to develop sophisticated timeline construction capabilities [46].

This distinction explains why:

- Unconscious systems (e.g., animals, artificial systems) can exhibit timeline-dependent behaviours without self-awareness [43].
- Conscious experience involves more than mere information processing; it includes subjective awareness of that processing [44].
- Temporal experience has both automatic and reflective components — automatic construction of sequences and reflective questioning of their meaning [47].

From the perspective of conscious experience, the IPTT defines:

- The **Past** as the realm of accessible memories — information that has been causally integrated into our self-narrative [24].
- The **Present** as the dynamic, constantly refreshing stream of sensory input and immediate cognitive processing, whose continuous updating underlies the subjective experience of ‘flow’ [35, 48].
- The **Future** as a probabilistic landscape of anticipation — constructed from predictive models of the brain based on past learning and current information [26].

This active construction of past, present, and future is central to our conscious engagement with reality, allowing us not only to navigate our environment effectively but also to imbue our experience with meaning and coherence [49].

6.2 Memory, Identity, and Personal Timelines

Personal identity is fundamentally tied to the construction and maintenance of coherent personal timelines [50]. This continuous process begins from a relatively ‘clean slate’ in early development and expands throughout life as more information is integrated into the timeline. The integrity of this timeline construction underpins the sense of self and continuity over time [49].

Various pathological conditions illustrate this connection:

Amnesia: Represents disruptions in the ability to access or construct segments of the personal timeline. Patients with amnesia cannot coherently integrate events from the affected periods into their self-narrative, leading to gaps in perceived identity continuity [45].

Dementia: Involves a progressive breakdown of timeline construction. As patients lose the ability to organise new and old information temporally, their sense of personal continuity and identity progressively deteriorates [51].

Dissociative Identity Disorder (DID): May involve the creation of multiple, parallel personal timelines that are not integrated into a single coherent sequence. Each identity maintains its own distinct timeline, reflecting fragmented self-narratives [52].

According to IPTT, the continuity of personal identity does not depend on metaphysical persistence ‘through time’ but on the ongoing construction of a coherent, causally connected personal timeline from memory traces and ongoing experience [49].

6.3 Altered States and Timeline Construction

The IPTT framework accounts for various altered states of consciousness as modifications to the normal processes of timeline construction [12].

Dreams: During sleep, the brain continues to process information, but primarily from internally generated sources such as memory fragments and spontaneous neural activity [43, 45]. This produces dream timelines that often feel subjectively extended, despite occurring over short physiological time intervals.

Coma Experiences: Some patients emerging from a coma report vivid, seemingly extensive experiences during their unresponsive state [44]. Within IPTT, this reflects continued (albeit impaired) timeline construction based on internal information streams. If the brain generates a dense sequence of memory traces during the coma, the resulting personal timeline may span what feels like decades, even though little external time has passed.

Meditation and Flow States: Meditative and flow states often involve alterations in the rate and focus of information-processing [53, 12]. These changes can modify timeline construction, producing subjective experiences of timelessness, expanded present moments, or distorted duration judgements.

Hallucinations: When the brain incorporates erroneous or false sensory data into its timeline construction, hallucinations result [25]. These internally consistent but externally inaccurate sequences appear temporally real to the individual because they are causally coherent within their personal information-processing system.

These phenomena further illustrate that subjective temporal experience arises from the constructive, observer-dependent timeline assembly, not from an absolute temporal flow.

7 Testable Consequences

A significant strength of the Information-Processing Theory of Time (IPTT) is its capacity to generate concrete, empirically testable predictions across various scientific disciplines. These predictions allow for the validation, refinement, and potential falsification of the theory [54].

7.1 Cognitive and Behavioural Phenomena

The IPTT predicts specific patterns in human temporal perception and memory based on the nature and density of information-processing [55, 4, 5].

Prediction 1: Information Density and Time Perception. Periods with higher information-processing density (i.e., more distinct observable changes or events processed per unit of objective time) should be perceived as lasting longer retrospectively [55, 11]. Conversely, periods of low information density (e.g., boredom or monotony) should also feel extended *during* the experience due to the brain actively registering the lack of change but remembered as shorter [55, 56].

- **Experimental Design — Cognitive:**

- **Participants:** Healthy adults.
- **Task:** Participants engage in two tasks for the same objective duration:
 - * **High Information Density:** A complex, rapidly changing task (e.g., fast-paced video game, novel stimuli).
 - * **Low Information Density:** A monotonous, predictable task (e.g., staring at a static image, repetitive button press).
- **Measurement:** After each task, participants estimate its duration.
- **Expected Outcome:** High-density conditions feel longer retrospectively; low-density conditions feel longer in-the-moment but are recalled as shorter.

Prediction 2: Attention and Timeline Construction. Divided attention or reduced cognitive resources allocated to an event stream should lead to fragmented timeline construction and impaired temporal discrimination [42, 57].

- **Experimental Design — Cognitive/Behavioural:**

- **Participants:** Healthy adults.
- **Task:** Observe sequences of distinct events under two conditions:
 - * **Full Attention:** Focus solely on sequence.
 - * **Divided Attention:** Perform secondary demanding task simultaneously.
- **Measurement:** Temporal discrimination (ordering, intervals) and timeline coherence (recall).
- **Expected Outcome:** Divided attention reduces accuracy and coherence of constructed timelines.

7.2 Neurological Correlates

IPTT predicts specific neural processes underlying timeline construction [16, 58].

Prediction 3: Neural Oscillation Patterns and Temporal Resolution. Higher coherence in neural oscillations (e.g., theta, gamma) should correlate with finer temporal resolution and more coherent timelines [57, 59, 60].

- **Experimental Design — Neuroimaging/EEG:**

- **Task:** Participants judge very fine temporal differences in stimulus sequences.

- **Measurement:** EEG/MEG recordings of oscillatory activity correlated with performance.
- **Expected Outcome:** Stronger theta/gamma oscillations in relevant regions (hippocampus, prefrontal cortex) predict more precise temporal judgements.

Prediction 4: Brain Lesion Effects. Damage to memory and integration areas (e.g., hippocampus) should impair timeline construction and coherence [45, 51, 34].

- **Experimental Design — Clinical Study:**

- **Participants:**
 - * Group A: Patients with hippocampal damage.
 - * Group B: Patients with non-hippocampal brain damage.
 - * Group C: Healthy controls.
- **Tasks:**
 - * **Immediate Timeline:** Recall order of short stimulus sequence.
 - * **Delayed Timeline:** Reconstruct narrative or event sequence after delay.
- **Expected Outcome:** Group A performs comparably on immediate tasks but worse on delayed, complex timelines.

7.3 Physical and Cosmological Implications

IPTT’s reinterpretation of time as emergent from information-processing has testable implications for fundamental physics [61, 22].

Prediction 5: Information Boundaries and Temporal Discontinuity. Boundaries that limit information accessibility (e.g., black hole event horizons, pre-recombination universe) should correlate with breakdown of constructed timelines for external observers [41, 10].

- **Experimental Design — Astrophysical/Observational:**

- **Methodology:** Astrophysical data and modelling.
- **Observation:** Analyse emissions from matter near black holes and model information flow at event horizons.
- **Measurement:** Search for observable signatures (e.g., distortions in light, gravitational wave echoes) indicative of information loss or smearing at the horizon.
- **Expected Outcome:** Consistent with theory, no information about events inside the horizon should reach an external observer, and observed phenomena near the horizon should reflect a breakdown of clear temporal ordering.

Prediction 6: Relativistic Effects and Information Processing Rates. Relativistic effects (e.g., time dilation) should manifest as measurable changes in rates of physical processes underpinning information-processing [28, 29, 3].

- **Experimental Design — High Precision Physics:**

- **Methodology:** Use atomic clocks in varying gravitational potentials or at high velocities.
- **Experiment:**
 - * **Gravitational Time Dilation:** Compare clocks at different altitudes [36].
 - * **Velocity Time Dilation:** Repeat Hafele–Keating-style experiments with refined clocks [32].
- **Expected Outcome:** Differential clock rates reflect differences in accumulated ‘observable changes’ (information).

7.4 Computational and AI Implications

IPTT provides a framework for designing artificial systems capable of constructing and navigating temporal realities [26, 25].

Prediction 7: Information-Processing Limits on AI Timelines. There are computational limits to an AI’s ability to construct coherent timelines, depending on its resources and input complexity [62, 63].

- **Experimental Design — Computational/AI:**

- **Methodology:** Build AI agents tasked with timeline construction from input streams.
- **Variables:**
 - * Input data rate and complexity.
 - * Available processing resources.
 - * Causal inference complexity [17].
- **Measurement:**
 - * Timeline coherence score (accuracy, consistency, completeness).
 - * Resource usage and latency.
- **Expected Outcome:** Timeline coherence degrades when input exceeds capacity, mirroring biological constraints.

These predictions underscore the interdisciplinary reach of IPTT, offering empirical pathways for investigation across physics, cognitive science, neuroscience, and AI [1, 14].

8 Comparison with Existing Theories

8.1 Block Universe Theory

The Block Universe (or Eternalism) treats all moments — past, present, and future — as equally real, offering a four-dimensional spacetime where time does not ‘flow’ [64, 65, 1].

However, this theory does not explain the subjective experience of temporal flow or the apparent asymmetry between past and future [2]. IPTT addresses this gap by attributing the sense of flow to active, ongoing timeline construction by information-processing systems, thereby resolving McTaggart’s paradox in a naturalistic way [66, 67].

8.2 Presentism

Presentism claims that only the present moment truly exists [68, 69]. While intuitively appealing, it struggles to account for the reality of historical records and the validity of predictions about the future, and faces serious challenges from relativity theory regarding the simultaneity of distant events [64, 8]. Within the IPTT framework, the ‘present’ is not ontologically fundamental but simply the current state of an observer’s information-processing. Past and future are constructed as integrated memories and predictive models, respectively, within this process [43, 24].

8.3 Growing Block Theory

Growing Block Theory asserts that the past and present are real, while the future is not yet real [70, 71]. It posits that the ‘block’ of spacetime grows as events occur. IPTT removes the need for such metaphysical growth by showing that timelines expand only as accessible information accumulates. The perceived ‘growth’ of time is thus a reflection of increasing information available for timeline construction, rather than an ontological property of the universe [13, 38].

8.4 Emergent Time Theories

Several approaches propose that time emerges from more fundamental, atemporal processes — for example, from thermodynamics, quantum decoherence, or causal set theory [22, 9, 72]. Carlo Rovelli’s relational quantum mechanics and thermal time hypothesis represent particularly sophisticated attempts to ground time in physical processes [18, 21, 14]. While aligned with the spirit of these views, IPTT differs in the following respects:

- It provides specific, operational definitions of temporal emergence rooted in information-processing, rather than purely thermodynamic or quantum mechanical foundations [73, 74].
- It generates clear, testable predictions spanning physics, cognitive science, and AI, connecting subjective temporal experience to fundamental physics [5, 4].
- It connects temporal emergence directly to information theory and the cognitive sciences, rather than purely physical principles, thereby bridging the explanatory gap between physics and psychology [35, 42].
- It offers concrete resolutions to specific relativistic and cosmological puzzles (e.g., simultaneity, time dilation, event horizons) by grounding them in information accessibility and processing rates [6, 41, 37].

Unlike theories that treat time as fundamentally illusory [22] or purely relational [61], IPTT acknowledges the reality of temporal experience while explaining its emergence from information-processing dynamics. This approach avoids both the metaphysical commitments of substantival theories of time and the counterintuitive implications of purely eliminative approaches [2, 1].

9 Philosophical Implications

9.1 The Nature of Temporal Flow

Our theory addresses the enduring puzzle of temporal ‘flow’ without invoking mysterious metaphysical processes. The profound human experience of time ‘flowing’ forward emerges directly from the sequential and active nature of **information-processing and timeline construction** by an observer, rather than from any objective, inherent movement through a pre-existing temporal dimension [66, 2, 14].

This framework offers a powerful resolution to **McTaggart’s paradox** [66], which highlights fundamental difficulties in reconciling the dynamic, ‘tensed’ view of time (the A-series, where events are constantly shifting from future to present to past) with the static, ‘tenseless’ view (the B-series, where events are simply ordered as ‘earlier than’ or ‘later than’). Our theory shows that neither the A-series nor the B-series, on their own, capture the fundamental nature of time [71, 67].

Instead, time fundamentally emerges from what we term the **C-series** — the **causally-driven process of information integration and reasoning** by which an observer constructs their internal timeline. It represents the continuous, active sequencing of detected changes based on their inferred causal relationships. The ‘flow’ we perceive is not an external, independent movement of moments but rather the subjective experience generated as new information is constantly acquired, processed, causally linked, and assimilated into an evolving internal representation of reality. This ongoing integration of information into a coherent, causally ordered sequence is the very essence of the C-series [2, 35].

The construction of these causally coherent timelines begins from a ‘clean slate’, analogous to an infant’s developing cognitive system. Initially, a baby builds its personal timeline from direct sensory experiences and early memories [43]. As development proceeds, the timeline expands to incorporate broader historical knowledge and collective narratives [34, 24]. Critically, for humans, the coherence and synchronisation of personal timelines on a global scale are achieved by anchoring them to universally agreed-upon, repetitive physical changes, such as the oscillations of caesium atoms in atomic clocks. Calendars and clocks thus serve as collective reference points, enabling multiple individual timelines to be synchronised by referencing shared physical events [1, 37].

9.2 Free Will and Temporal Agency

The theory also has implications for debates about free will. If timelines are constructed rather than discovered, then the future is not a fixed structure awaiting revelation but something constructed through ongoing information-processing and decision-making. This

perspective challenges both hard determinism and libertarian free will by suggesting that temporal agency emerges from the very process of information integration and causal reasoning [1].

This suggests a **compatibilist** position in which deterministic physical processes enable timeline construction, while the construction process itself involves genuine choices about how to organise and interpret information — effectively granting agents temporal agency within physical constraints. The brain’s predictive processing mechanisms [25, 26] play a crucial role in constructing potential futures, making the act of temporal construction itself a form of agency that operates within, rather than outside, the causal order of nature.

9.3 Personal Identity and Temporal Persistence

Traditional theories of personal identity often grapple with metaphysical challenges, relying on continuity of substance, consciousness, or memory through time [75, 76]. The Information-Processing Theory of Time (IPTT) offers a novel and naturalistic account: **personal identity fundamentally consists in the ongoing construction and maintenance of an individual’s coherent personal timeline.**

To unpack this:

- **What constitutes a ‘coherent personal timeline’?** This refers to the integrated, causally linked, and continuously updated sequence of an individual’s memories, experiences, beliefs, and learnt information. It is the unique, evolving narrative that a specific information-processing system (a person’s brain) actively builds — comprising ‘what happened to me, when it happened, and why’. This timeline is coherent because the brain strives to organise information into causally meaningful sequences, making sense of events in relation to one another and the self [52, 49].
- **How does this construction occur?** This is an **ongoing, dynamic process** driven by the brain’s continuous processing of new sensory input, internal states, and reflective thought [42, 77]. As new information is acquired, it is not merely appended but actively integrated, categorised, and positioned within the existing personal timeline — constantly updating and refining the narrative of the self across perceived time. This construction leverages the brain’s capacity for memory formation, information integration, and causal reasoning (as outlined in Principle IV: Causal Inquiry Dependence). The brain continually works to maintain a consistent self-narrative by linking past experiences to present perceptions and future expectations within this evolving temporal structure [50, 51].

This information-centric approach provides a powerful naturalistic account of personal persistence. It avoids traditional metaphysical puzzles about identity criteria (e.g., the ‘Ship of Theseus’ paradox or reliance on an unchanging soul) by rooting identity in an active, dynamic process of information organisation [75]. The ‘same person’ persists because their unique, causally coherent personal timeline continues to be actively constructed and maintained — integrating new experiences into the evolving narrative of ‘who I am and what I have experienced’ [76, 24].

This account also naturally explains phenomena that challenge traditional theories of personal identity, such as cases of severe memory loss or multiple personality disorder, as disruptions to the coherent construction of personal timelines rather than mysterious breaks in metaphysical continuity [43, 52].

10 Future Research Directions

The Information-Processing Theory of Time (IPTT), as presented, lays a foundational framework for reconceptualising time as an emergent property of information-processing. Like any robust theoretical framework, it not only offers explanations for existing phenomena but also opens up vast and fertile ground for future inquiry. The following research directions stem directly from the core tenets of the IPTT, aiming to further validate its claims, expand its theoretical scope, and explore its profound practical implications across various scientific and applied domains.

10.1 Empirical Research Programs

Neuroscience Studies: Investigate neural correlates of timeline construction using advanced neuroimaging techniques. Identify brain networks specifically involved in temporal sequence construction as distinct from other forms of information-processing [16, 5, 58]. Research should focus on how different brain regions contribute to the integration of temporal information and the construction of coherent temporal narratives [51].

Cognitive Psychology Experiments: Design controlled studies testing predictions about temporal perception under various information-processing conditions. Examine how different types of information contribute to timeline construction and how disruptions (e.g., divided attention, sensory deprivation) alter perceived time [55, 4, 11]. Investigate the discrete versus continuous nature of time perception [57, 59] and how emotional states influence temporal experience [11, 12].

Artificial Intelligence Research: Develop AI systems explicitly tasked with constructing timelines and investigate whether they exhibit analogues of temporal experience. Such studies could illuminate the computational requirements for coherent timeline construction and potentially inspire more temporally-aware AI agents [78, 63, 62]. Focus on how predictive processing frameworks [26] might inform the development of AI systems with temporal awareness.

10.2 Theoretical Developments

- **Quantum Mechanics Integration:** Explore connections between quantum measurement processes and timeline construction. Specifically, investigate whether **quantum decoherence** plays a fundamental role in defining the discrete, definite ‘events’ from which a classical timeline can be built [73, 74]. Without decoherence, a system may exist in a superposition of states; it is only through decoherence that a singular, classical outcome (an ‘event’ in our timeline) is realised. This irreversible process of ‘event

actualisation’ could directly contribute to the perceived directionality of temporal experience, as each decohered event adds an unchangeable, definite element to the past. This approach aligns with relational quantum mechanics perspectives on the observer-dependent nature of physical events [18].

- **Information Geometry:** Develop geometric frameworks for understanding timeline construction in an **information space** [79]. This entails applying the mathematical tools of differential geometry (e.g., distance, curvature, geodesics) not to physical space but to spaces representing **probability distributions of events, information states, or possible causal orderings**. Such models could quantify the ‘distance’ between different timelines, characterise the ‘shape’ of an observer’s information landscape, and rigorously analyse how observers construct and navigate their temporal relationships. This mathematical approach could provide quantitative tools for understanding causal inference [17].
- **Complexity Theory:** Investigate **computational complexity bounds** on timeline construction and their implications for temporal experience [80, 81]. This includes analysing the **inherent resource requirements** (e.g., processing time, memory) for an information-processing system to observe, store, and organise changes into a coherent timeline. Such bounds could explain the **limits of an observer’s temporal resolution, the fidelity of their constructed timeline, and why certain temporal judgements are computationally challenging or impossible** for biological systems. This connects to broader questions about the computational limits of cognitive processes [47].

These theoretical developments — integrating quantum mechanics, leveraging information geometry, and applying complexity theory — offer a deeper, more rigorous understanding of the mechanisms underlying timeline construction and temporal experience. While abstract, these insights have the potential to inspire novel applications across disciplines.

10.3 Interdisciplinary Applications

- **Clinical Applications:** Develop new approaches to treating temporal disorders based on understanding the mechanisms of timeline construction. Individuals with conditions such as **schizophrenia** often experience distorted temporal perception and fragmented self-narratives [82, 83, 15]. By identifying specific information-processing deficits (e.g., in causal coherence or memory integration) underlying these distortions, targeted interventions could be designed to improve temporal experience and personal coherence. This approach builds on research showing the critical role of temporal processing in mental health [56].
- **Technology Design:** Apply insights from timeline construction theory to develop better human-computer interfaces and artificial intelligence systems. By designing AI systems that construct their own adaptive timelines — guided by principles of **causal coherence** — we can create more intelligent and adaptable agents capable of learning effectively from experience, making accurate predictions about future events,

and engaging in human-like temporal reasoning [78, 63, 62]. This connects to broader research on predictive processing and the free-energy principle [25, 26].

- **Education:** Investigate how understanding timeline construction could improve learning and memory techniques. By leveraging insights into how the brain naturally organises information into **causally coherent sequences**, educational strategies could be developed to enhance students’ ability to build robust, long-lasting mental timelines for new knowledge, thereby improving comprehension and retention [77, 51]. This approach could incorporate findings from research on working memory [42] and episodic memory formation [34, 45].

11 Conclusion

We have presented a comprehensive theory of time as an emergent property of information-processing and timeline construction. This framework offers fresh perspectives on fundamental questions in physics, neuroscience, and philosophy whilst making specific, testable empirical predictions. The theory’s key contributions include:

- **Conceptual Unification:** A unified framework for understanding temporal phenomena across multiple disciplines, from relativistic physics to cognitive neuroscience [1, 14].
- **Problem Resolution:** A coherent, information-theoretic resolution to long-standing paradoxes about the nature of time, simultaneity, and cosmological origins [66, 67].
- **Empirical Testability:** Unlike many theories of time, the IPTT makes precise predictions that can be experimentally investigated. For example, it predicts that disrupting specific neural oscillation patterns—critical for information binding—should impair temporal resolution. This could be tested using non-invasive brain stimulation techniques such as **transcranial magnetic stimulation (TMS)** to selectively disrupt these oscillations, followed by measuring participants’ ability to discriminate durations or temporal sequences [5, 60, 59].
- **Practical Applications:** Novel approaches to understanding temporal disorders, advancing artificial intelligence, and informing educational and clinical practices [82, 15, 63].

Clarifying Epistemic vs. Ontological Components: We explicitly distinguish between:

- **Ontological substrate (t):** A coordinate parameter describing ordered physical state changes (e.g., proper time in relativity) [6, 7]. This is static, without ‘flow’, and independent of observation.
- **Epistemic timeline (T_S^*):** An emergent, subjective, flowing timeline constructed by an observer through the integration of accessible information [18, 24].

Summary of the Information-Processing Theory of Time (IPTT)

The theory suggests that time is neither an absolute container nor a fundamental dimension of spacetime but rather the inevitable result of information-processing systems organising their observations of change [22, 14]. This perspective renders time both more mysterious—as it emerges from complex cognitive and physical mechanisms—and more comprehensible—as it reduces to principles that can be empirically studied and mathematically formalised [9, 2].

Perhaps most significantly, this framework suggests that time is not merely something that happens to us but something we actively create through our ongoing engagement with the changing world [49, 52]. Every observation, every memory, and every causal inference contributes to the construction of the temporal reality within which we exist [34, 24].

This perspective opens new avenues for research and offers practical applications in fields ranging from neurology to artificial intelligence [25, 26]. Most fundamentally, it provides a naturalistic account of one of reality’s most basic features while preserving the richness and complexity of temporal experience [35, 12]. Understanding how we construct our temporal reality may lead to new treatments for disorders of temporal perception [82, 83], deeper insights into the nature of consciousness [46, 44], and innovative designs for artificial systems capable of engaging meaningfully with temporal relationships [62, 63].

As we continue to investigate the mechanisms of timeline construction and their connection to physical processes, this theory not only illuminates the nature of time but also promises insights into the fundamental nature of information, consciousness, and reality itself [73, 61, 1].

Key Aspect	Description / Implication
Fundamental Nature	Time is not an absolute dimension but emerges from the observation, storage, and sequential organisation of changes by information-processing systems.
Observer-Dependence	Each system constructs its own timeline (T_S^*) based on its unique accessible information ($\mathcal{I}_S$), leading to observer-relative but physically consistent temporal realities.
Causal Coherence	The constructed timeline is an optimally coherent causal ordering (T_S^*), driven by the system’s imperative to establish causal relationships.
Flow of Time	The subjective experience of time ‘flowing’ arises from the dynamic, continuous process of integrating new information and causal inferences (the C-series).
External Parameter	The parameter t is an abstract, external metric for measuring processing rates, distinct from the emergent time constructed by the observer.
Resolution of Paradoxes	Provides naturalistic resolutions to the Twin Paradox (differential information processing rates), McTaggart’s Paradox (via the C-series), and cosmological origin questions (information horizons).
Empirical Basis	Makes testable predictions regarding neural oscillations, brain lesions, relativistic effects, and computational limits of timeline construction.
Interdisciplinary Scope	Bridges physics, neuroscience, cognitive psychology, and philosophy of mind and offers implications for clinical practice, AI, and education.

Table 1: Summary of the Information-Processing Theory of Time (IPTT).

12 Limitations and Open Questions

While the Information-Processing Theory of Time (IPTT) offers a unified and compelling framework, it remains a nascent theory and, like all ambitious scientific endeavours, carries inherent limitations and raises numerous avenues for further inquiry.

One key challenge lies in the empirical verification of its fundamental tenets, particularly the precise mechanisms underlying the **Causal Coherence Function ($\mathcal{C}$)**. Given that no two human brains are identical, and each may employ subtly different ‘algorithms’ for processing and ordering events [51, 16], direct and universal testing of $\mathcal{C}$ is exceptionally complex. Factors such as individual biases (e.g., whether a person trusts their own intuitive judgments over external expert input when confronting ambiguous temporal sequences) introduce

substantial variability, making simple, uniform empirical measurement extraordinarily difficult—if not impossible [55, 47]. Research may therefore need to focus on identifying general principles and patterns rather than attempting a single, universal quantification of $\mathcal{C}$.

While the theory outlines several testable predictions (e.g., neural oscillation patterns, effects of lesions), directly measuring ‘information-processing events’ at the most granular level or universally quantifying ‘causal coherence’ remains a significant experimental hurdle [5, 59]. The theory’s abstract and interdisciplinary nature demands sophisticated experimental designs and advanced analytical tools for its full empirical validation [58, 15].

Furthermore, the theory primarily focuses on the **subjective and constructed aspects of time**. While it explicitly connects these to objective physical processes (e.g., time dilation [28, 29], quantum decoherence [74, 73]), the precise ways in which these physical realities constrain or enable specific forms of information-processing remain underdeveloped. For example, questions about the ultimate physical ‘ground’ of information itself or how the universe behaved before the emergence of any complex information-processing systems remain beyond the present scope of the IPTT—though the ‘information horizon’ concept provides a pragmatic boundary condition for such considerations [19, 10].

The relationship between the theory and established physical frameworks presents additional challenges. While preliminary connections to quantum mechanics are proposed [18, 23], a deeper and more formal unification with quantum gravity theories remains a significant theoretical challenge [61]. The theory must also grapple with the fundamental thermodynamic arrow of time [9, 10] and how this relates to the constructed timelines of information-processing systems.

Finally, integrating the theory with neuroscientific findings presents both opportunities and challenges. Identifying the precise computational mechanisms and neural architectures that enable complex timeline construction in biological brains will require extensive future neuroscientific research [82, 83]. The theory must account for the variety of temporal processing disorders observed in clinical populations [56, 15] and how these relate to specific information-processing deficits.

The philosophical implications of the theory also require further development. Questions about the relationship between constructed timelines and personal identity [75, 52], the nature of temporal experience in non-human information-processing systems, and the ultimate metaphysical status of time itself [66, 1] remain open areas for investigation.

These limitations are not weaknesses but rather define the exciting frontiers for future research, inviting interdisciplinary collaboration to refine, expand, and rigorously test the full implications of time as an emergent information-processing phenomenon [67, 14].

13 Potential Criticisms and Responses

Any novel theoretical framework, especially one addressing a concept as fundamental as time, is subject to scrutiny and potential criticisms. This section anticipates some common objections and provides counterarguments within the scope of the Information-Processing Theory of Time (IPTT).

1. Criticism: ‘The theory is too abstract and lacks empirical support.’

- **Response:** While the IPTT indeed proposes a deep reconceptualisation of time, it

is not merely abstract philosophy. Crucially, the theory makes **specific, falsifiable predictions** that can be experimentally investigated across neuroscience, cognitive psychology, and artificial intelligence. For example, predictions regarding the correlation between neural oscillation patterns and temporal resolution [59], or the effects of localised brain lesions on timeline construction [58], are directly amenable to empirical testing. Moreover, recent studies in cognitive neuroscience and computational models of perception have already begun to provide indirect evidence supporting the role of information integration and causal inference in our subjective experience of time [56]. The IPTT provides a concrete research programme for empirical validation, moving beyond purely speculative accounts.

2. Criticism: ‘The IPTT only explains subjective or psychological time, not fundamental physical time or the “objective” flow of time.’

- **Response:** This criticism misunderstands a core tenet of the IPTT. The theory argues that the very concept of an ‘objective flow’ of time, independent of information-processing, is a misconception. What appears as ‘objective physical time’ (e.g., atomic clock readings, proper time in relativity) is understood within the IPTT as a measurable sequence of physical changes or events that provide the **raw information** for systems to construct their timelines. The theory integrates these physical realities — like relativistic time dilation, which describes how physical processes themselves occur at different rates — by showing how they lead to differential information acquisition and thus genuinely different constructed timelines for observers [14]. Therefore, the IPTT does not merely explain subjective time; it proposes that *all* experienced and measured time, whether individual or collective, is fundamentally a consequence of information-processing and construction, resolving the apparent dichotomy between subjective and objective temporal accounts.

3. Criticism: ‘The theory is circular because information-processing itself requires time.’

- **Response:** This apparent circularity is resolved by distinguishing between the emergent, constructed timeline and the underlying physical substrate. The information-processing that builds the emergent timeline does not require a pre-existing flowing or emergent temporal dimension. Rather, it depends on the physical ordering of changes in the substrate — that is, the sequence of states that the spacetime manifold encodes [2]. This ordering can be parametrized by an external coordinate, which serves only as a convenient index of physical configurations. The IPTT explains how a coherent, causally ordered, and flowing timeline emerges as a subjective construction from these ordered physical events — not that the events themselves require an absolute or flowing time to occur. The emergent ‘time’ of experience is thus the observer’s interpretation and organization of the physical sequence of events, not a fundamental dimension of reality.

4. Criticism: ‘How does the theory account for time or events in the absence of any information-processing observer?’

- **Response:** The IPTT primarily describes the nature of *experienced and constructed* time. In the absence of an information-processing system, the physical universe still undergoes changes and interactions. These changes themselves are the ‘raw material’ for potential timeline construction. For instance, stars still burn, galaxies still expand, and fundamental physical processes occur according to the laws of physics. However, without an entity capable of observing, storing, and organising these changes into a coherent, causally linked sequence, there is no *emergent timeline* in the sense defined by the IPTT [22]. The universe would exist as a series of physically ordered changes, but without a subjective or collective temporal reality being actively constructed from them. The theory argues that ‘time’ as we know it is inherently tied to the act of observation and processing.

In conclusion, while the Information-Processing Theory of Time faces potential criticisms, the counterarguments presented here demonstrate its robustness and potential to provide a novel and comprehensive understanding of time. By addressing these objections and continuing to refine the theory through empirical research and interdisciplinary collaboration, we can further unlock the mysteries of time and its role in shaping our reality.

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Conflict of Interest Statement

The authors declare no competing interests.

Data Availability Statement

This theoretical work does not involve empirical data requiring public archiving.

Ethics Statement

This theoretical research does not involve human subjects requiring ethical approval.